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Investigation of possible societal risk associated with wind power generation systems

F.O. Moura Carneiro, H.H. Barbosa Rocha, P.A. Costa Rocha *

Laboratory of Aerodynamics and Fluid Mechanics (LAero), Department of Mechanical Engineering, Federal University of Ceará, Campus do Pici 715, Fortaleza/CE 60440-554, Brazil

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A B S T R A C T

There is a progressive acceptance about the proposal of wind as an alternative source of energy to meet future global demand and significant reduction of environmental pollution. In this context, from design to decommission, safety doubtless represents an integral element of wind turbines. Based on historical accident data the quantitative risk measure of societal risk in connection with wind farms was evaluated in the present work. It was considered the CWIF database which contains information on accidents, incidents and fatalities related to wind technology from the 1970s to October 2011. The data were presented in its absolute values and normalized by the capacity of wind power installed worldwide over the years. The security level observed due to the wind turbine operation tends to increase with the increment of installed capacity. The social risk was calculated for two particular cases (characteristically arbitrary). As observed by the results (the curves in the F–N diagram) obtained for both scenarios, the risk does not exceed the upper limit of ALARP criterion. Nonetheless, the required application of principles for the integration of safety to tackle the hazards linked with wind turbines must not be neglected. Safety must be increased as the wind energy production expands, as well as there should be a need for regular reconsideration.

Contents

1. Introduction

As a renewable source of energy, the wind provides a significant contribution to renewable energy targets. Wind power industry has been developing rapidly, and high penetration of wind power into grid is taking place, which directly pushes the wind technology into a more competitive area [1]. Due to a singular technical identity, wind turbine technology has an unique demand in terms of methods used for design [2].

Among its benefits the wind energy has no radiation hazards, the source is free, incurs no transport costs and produces some of the lowest rates of pollution/thermal emissions for electric-power generation into the atmosphere or nearby water resources. Currently (October 2012) the worldwide capacity of installed onshore wind farms stands at more than 250 GW (and above 280 GW involving offshore projects) [3] with a sustained growth rate predicted over the present decade. Maintaining such growth necessitates research into the management of economic and environmental risks associated with the operation of large-scale commercial wind ventures [4].

* Corresponding author.
E-mail address: paulo.rocha@ufc.br (P.A. Costa Rocha).

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Unquestionably, safety as an integral element of the turbine – from design to deployment – must always be in the foreground. Wind turbines are extremely sophisticated machines. The vertical tower (which carries the key components of the wind turbine inside the nacelle, e.g. the gearbox, mechanical brakes, electrical generator, control systems, etc [1]) and the turbine rotor (consisting of rotor blades and hub) are the main components subjected to highly variable forces as the blades rotate. As the wind speed changes, the variation in the forces increases, resulting that these components are subjected to severe fatigue [5,6]. Therefore, to help with their decision-making process, managers of health care, the environment, and physical infrastructure systems should all incorporate risk analysis [7]. There are several commonly used measures of risk, so the question arises as to which should be used.

Apropos, the term risk usually expresses not only the potential for an undesired consequence, but also how probable it is that such a consequence will occur, while the term hazard expresses the potential for producing an undesired consequence without regard to how likely such a consequence is [8]. Risk has been considered as the chance that someone or something that is valuated will be adversely affected by the hazard [9], while hazard is any unsafe condition or potential source of an undesirable event with potential for harm or damage [10]. Risk management is a tool that can be used to determine the risks associated with the hazards in any work process, machine, or chemical process. Risk assessment is a part of risk management. Once the hazards are identified, the risk assessment can be performed. Furthermore, risk assessment is an essential and systematic process for assessing the impact, occurrence and the consequences of human activities on systems with hazardous characteristics [11]. It constitutes a needful tool for the safety policy of a company, keeping in mind that completely controlling behaviors through rigid and voluminous procedures cannot be done. This happens because of the complex nature and design of the equipment and the complexity of facilities [12]. To put it another way, there is a basic recognition that "zero risk" is not attainable and that the real aim must always be to identify, control and reduce the risk. Contrasting, there is still a belief that application of good practice embodied in design and other standards removes risk [13].

The main contribution of this work is the presentation of the quantitative measure of possible societal risk associated with wind turbines based on documented historical accident data. While statistics on accident rates (accident per inventoried capacity per year) should be considered inaccurate, these data may give a satisfactory description of the types of accidents which can occur, as well as their consequences. Thus the societal risk conceptual framework, traditionally applied in part of risk assessment task developed in industries such as chemical, nuclear, oil, and gas, is verified in the context of the wind energy systems technology.

This paper is organized as follows. After the introduction, in Section 2 the societal risk technique and ALARP principle are summarized. In Section 3, it is outlined some of the types of accidents related to wind turbine technology. In Section 4, the historical data are presented and examined and finally the conclusions of the present paper are stated in Section 5.

2. Quantitative societal risk technique

The individual risk (IR) can be defined as the probability (frequency) of lethality for an unprotected person in the vicinity of hazardous location [7]. Nonetheless, there are situations not completely described by IR technique, as is the case of a single accident that could result in fatality (or injure) to a large number of people. These situations can be addressed by estimating the societal risk (SR), expressed as a relationship between the accident scenario (an accident category), the frequency of this scenario (evaluated as probability per time unit), and the consequences (the number of injuries and fatalities) [14].

Several advantages count in favor of SR technique [7]:

- It is easy to apply
- It usually encompasses both public and worker risk
- It depicts the historical record of incidents
- It is both a quantitative and graphical technique
- The information about societal risk is illustrated by simple F–N diagrams
- It depicts criteria for judging the risk tolerability
- The system is characterized as tolerable or intolerable graphically and easily
- It provides a consistent basis to analyze the individual and societal risk.

Aforementioned, SR is usually represented as an F–N curve. In such a graph, it is plotted the expected (annual) frequency (F) of the number of casualties (N). The whole surrounding area (arising from all possible dangerous incidents at a hazardous site) is considered. Three regions are deemed in the F–N diagram:

(1) The risk is so high that it is intolerable
(2) An intermediate level where the ALARP (As Low As Reasonably Practicable) principle applies
(3) The risk is so low that it is considered negligible (or acceptable) [15].

In region 2, the so-called ALARP principle is adopted. An ALARP evaluation process will include a dedicated search for possible risk reducing measures, and a subsequent assessment of these in order to determine which should be implemented [16]. Nowadays widely applied in safety decision-making, the ALARP principle requires that those responsible for safety in the workplace – and, indeed, public safety – should reduce risks to levels that are "As Low As Reasonably Practicable". As such, the principle involves effective recognition of the fact that, while in most circumstances risk can be reduced, beyond some point further, risk-reduction is increasingly costly to implement [17]. The ALARP criterion is considered a more fundamental approach to the setting of tolerable risk levels and should be particularly suitable for regulatory purposes [15,18].

3. Accident hazard scenarios

The identification of the hazard exposure that may be encountered during the execution of a task or a job constitutes the primary purpose of a hazard/risk evaluation [12]. Therefore, some pertinent questions addressed when performing the identification of hazards related to onshore wind turbine plants can be listed:

- The kinds of risks caused by wind turbines
- The distance at which vulnerable objects need to be considered in the risk analysis
- The probability of a person or object be hit by a turbine fragment and
- The safety and risk criteria that are valid and should be met.

Studies were carried out to assess the damages to wind turbines and their components. Superficial cracks, geometric concentrator (the local geometry of stress concentrator in the

transition between the root area and the aerodynamic/airfoil profile area), and abrupt change of wind turbine blades thickness [19] reveal that the nature of these damages was probably due to a fatigue mechanism. According to [19], regardless the occurrences, the presence of diverse manufacturing defects could contribute to a decrement in the fatigue life of the element. As suggested elsewhere [20], the delamination at well-defined laminae interfaces associated with geometric imperfections is the major failure mechanism.

Wind farms installed in some of the best wind sites around the world (in regions with northern climate or at high altitudes) are facing possible icing events [21]. Commercially produced anti-icing or de-icing systems have not yet been proven reliable. Some manufacturers prefer to use special coatings of the blade's surface instead of heating systems [22] given the reported damage of prototypes [23]. Ice thrown from rotating blades poses a serious safety issue, particularly when the wind power plant site is near public roads, housing, power lines, and shipping routes [4].

In addition to ice adhesion and accretion on the blades (and supporting structure) of wind turbines, the wind energy industry presently faces two major challenges concerning the surface engineering of blades: insect accumulation on blades, and the erosion of blades by sand and water droplets. Wind turbine performance, as well as the security, can be significantly reduced when the surface integrity of the turbine blades is compromised [4].

Beyond blade/structural failures, ice throw and environmental damages, other documented accident causes include fire, transport, and assorted motives like component failure without consequential structural damage, electrical failure (not led to fire or electrocution), construction, etc [24].

Some of the adverse effects to the environ (human beings and wildlife) are highlighted in the next subsection.

3.1. Social and environmental impacts

Albeit the strong environmental bias, the negative impacts on human beings and wildlife, undoubtedly or presumably resulting from wind technology in-service, are object of recent researches.

Among the most frequent concerns are listed [25,26]: aesthetic and occupation of the landscape (negative perception), shadow flicker from wind turbines (probably causing headaches), electromagnetic interference (disturbances in some equipments in airplanes and buildings), and noise emissions.

Wind farms are unique sound sources and exhibit special audible and inaudible characteristics that can be described as modulating sound or as a tonal complex [27]. According to [28,29], wind turbines generate low frequency sounds that affect the ear, as well as infrasound (typically inaudible). Both low frequency and infrasound could represent adverse impacts from human exposure to wind turbines, which diseases/symptoms include chronic sleep disturbances, anxiety, stress and other aberrant behaviors [27]. It is argued that the experience of these adverse health effects to the environs (even at distances considered acceptable by regulatory authorities [30]), probably due to industrial wind turbines, implies in the loss of social justice [31–33]. Despite the claims about enough evidence related to the hazards of wind turbines noise, among the researchers there is a consensus about the need for more research to confirm/validate the grievances. The hazards applicable to human and animals attributed to wind energy systems are collectively referred as "wind turbine syndrome", itself a controversial topic [34].

The threats that wind farms can pose to wildlife, specifically birds, bats and raptors (birds of prey), are object of intense research [35,36]. For birds the risk appears to be the collision in the towers or blades of wind turbines, while for bats is to suffer from barotrauma (sudden pressure fluctuations in the lung) [37]. To guide future planning of wind farms, as well as in the management of currently operating energy systems, it is suggested a local inspection of the relationship between mortality at existing wind turbines and their relative position within the spatial distribution of bird populations. [38]. The aggregation of wind turbines in power plants and their avoidance in locations where (admittedly) birds concentrate could minimize their impact on biodiversity [39]. Also in this study [39], how losses due to collisions affect bird and bat populations and how the spatial configuration of wind turbines in the landscape affects them are the questions addressed. In general, birds are exposed to or at risk mainly during migrations [35]. Compared both to another energy sectors (nuclear, oil and gas) and to the causes of bird kills in the United States (cats, buildings, hunters, vehicles, communications towers, pesticides) [36] and Europe [37], the wind industry presents the lowest rate of casualties.

Some of the efforts performed by wind energy researchers to tackle such impacts are presented in [26,36].

3.2. Safety distances

The most serious failure from the safety point of view is the detachment of a blade or blade fragment (or even the ice on the blades) which could be thrown at a considerable distance and could damage people or properties [40]:

- Tumbling fragments could go as far as 800 m in extreme conditions, but, more likely, 370 m or less
- Gliding fragments could, correspondingly, go up to 2250 m, but are more likely to travel less than 1650 m.

In all cases, the probability of striking a fixed target with a blade fragment is less than 10^{-7} per year. In most cases and places the risk is much less than that [40].

For these reasons, it is recommended that wind turbines should be kept at least 60 m from railway lines, 90 m from pipework, 100 m from dykes and between 40 and 100 m from electric-power cables [41].

A minimum safe distance between new turbine developments and occupied housing and buildings currently is 2 km in Europe, being imposed in France a 500 m exclusion zone around operational turbines [24].

4. Data analysis and discussion

A useful help with the identification of possible hazards can be provided by the historical analysis of events involving a technical system under investigation. It was performed the historical analysis specifically on wind turbine accidents using the CWIF (Caithness Windfarm Information Forum) database [24]. This database includes all documented cases of wind turbine related accidents that can be found and confirmed through press reports or official information releases. Such events include human casualties or damages to the plants, properties or the natural environment.

The analysis allowed the identification of the most diffused causes (historically). First, according to CWIF database [24], the main consequences of accidents and/or incidents can be classified into two groups: damage to life (impacts on wildlife, human injury, fatal accidents) and damage to property (blade failure, miscellaneous causes, fire, structural failures, transport, icing). In incidents, there may not be the involvement of victims. It should be emphasized the importance of the databank for definition of the accident profile that occurs at wind industry, being the risk characteristically physical in nature.

Fig. 1 presents the historical evolution of the total accidents, given in absolute numbers. In the same figure, these absolute values are parameterized by the global installed onshore wind power generation capacity of the respective year (from 1995 to October 2011). Until October 2011, there was a total of 1093 records of accidents and/or incidents related to the wind industry sector. The analysis of the available data suggests that the security level attained progresses concomitant to the wind industry advancement during each corresponding period. While in absolute numbers the accidents oscillate and exhibit a trend to grow, the parameterized data indicate a different direction, pointing to the decrease of accidents related to wind installed capacity. The parameterized results indicate rapid expansion of the wind industry without, however, greater attention to safety issues. Since 2002, concomitant to the progress of wind technology, the security issue seems to be addressed, given the apparent decrease in the number of accidents in relation to the installed capacity.

The absolute number of fatalities and its parameterized value by the installed wind power generation capacity of the respective year is illustrated in Fig. 2. Compared to Fig. 1, a similar trend can be observed: the declination of the number of victims of accidents in wind sites from 2000, after the tech boom. Nonetheless, in absolute numbers, casualties also present a cyclic oscillatory growth trend over the years.

According to Fig. 3, blade failure (the most frequently identified occurrence, 20%), structural failure, miscellaneous causes, fire, negative impacts on wildlife, transport and ice throw represent altogether 85% of the accidents/incidents recorded in the database. The accidents involving humans (15%) can be classified as injuries (8%) and fatalities (7%). Considering human injuries, 72% of the accidents occurred to workers of the wind industry or small turbine owners/operators (hereafter direct partners), and 28% of the accidents occurred to the public, including workers not directly dependent on the wind industry (third parties). Taking into account fatal accidents, 82% occurred to direct partners and 18% involved third parties.

The distribution of the occurrences resulting in fatal accidents (80) for direct partners and third parties is presented in Fig. 4 and Table 1. The number of fatalities involving more than one person is larger for direct partners (58) than for third parties (17). In this case, the number of accidents is equal to the number of fatalities. Separately, according to the data presented in Table 1, it was observed that for direct partners 96.67% (58/60) of accidents involved one death, whereas considering third parties, this percentage is equal to 85% (17/20). This suggests that fatal accidents in which there is more than one death occur more frequently for third parties (15%) than for direct partners ($\sim 3\%$). The total number of deaths attributed to the wind technology is given by

$$\sum A \cdot N = [(17+58) \cdot 1] + [(2+1) \cdot 2] + [1 \cdot 3] + [1 \cdot 4] = 88. \qquad (1)$$

Of this casualties, 63 ($58 \cdot 1 + 1 \cdot 2 + 1 \cdot 3$) occurred to direct partners while 25 ($17 \cdot 1 + 2 \cdot 2 + 1 \cdot 4$) are related to third parties. Compared to the number of fatal accidents involving direct partners, the occurrences related to third parties cannot be considered insignificant.

The risk tolerability can be judged as individuals knowingly take and accept risks all the time. In general, by reference to known statistics about such risks, it is accepted that risk of death or serious injury should not exceed 10^{-5} in any year and that risk below 10^{-6} is negligible in relation to other accepted. Between these limits, the risk arising from a hazard must be made "as low as reasonably practicable" (ALARP). According to particular sensitivities, different countries have adopted different thresholds, having in common the setting of an acceptability ALARP area [42].

In this work, the societal risk (SR) technique is applied considering the capacity of power generation by a wind power system, according to the following equation:

$$SR = \left(\frac{A \cdot N}{B \cdot C}\right) \cdot P, \qquad (2)$$

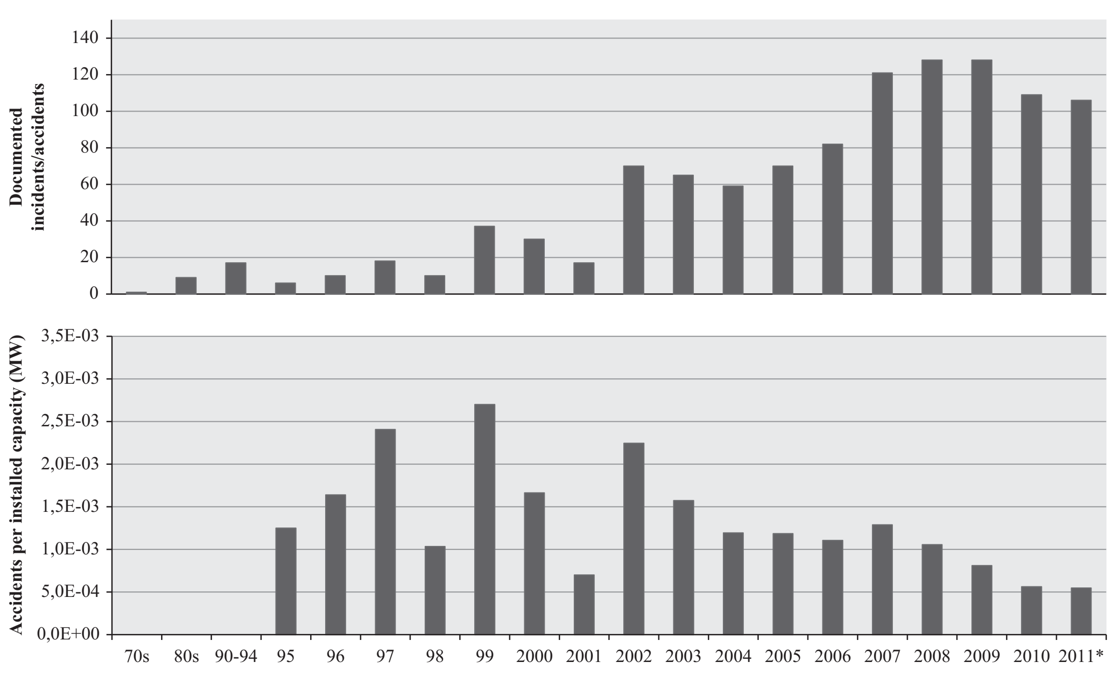

Fig. 1. Annual evolution of total accidents/incidents occurred related to wind power industry in absolute numbers (top) and parameterized by the installed capacity (bottom) (source: [24] *Summary of wind turbine accident data to 1st October 2011).

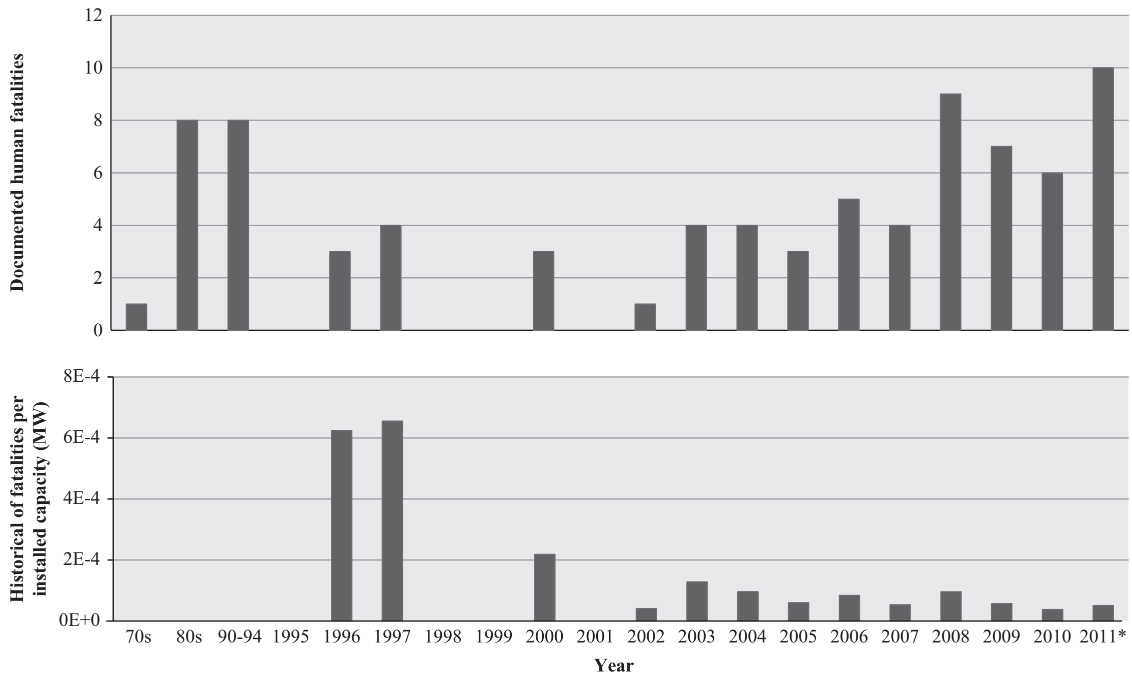

Fig. 2. Annual evolution of human fatalities occurred related to wind power industry in absolute numbers (top) and parameterized by the installed capacity (bottom) (source: [24] *Summary of wind turbine fatal accident data to 1st October 2011).

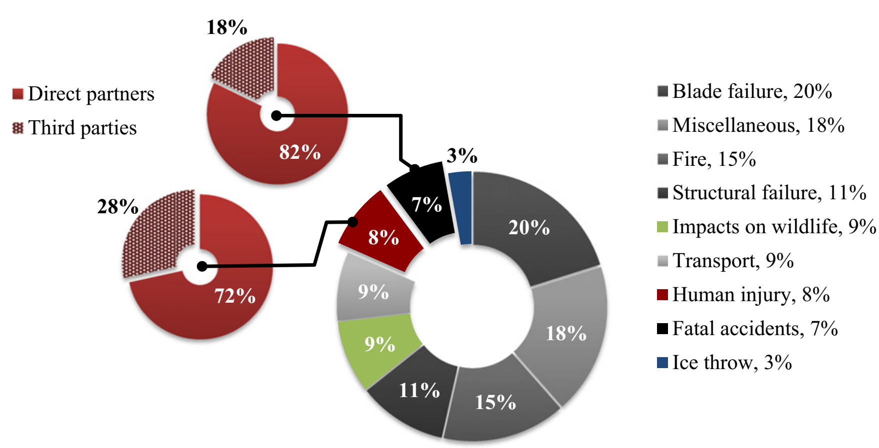

Fig. 3. Shares of documented consequences of accidents involving wind turbines. Human injury and fatalities consequences divided between direct partners and third parties.

where A is the cumulative number of accidents involving $N=1$, 2, 3 or 4 fatalities, B is the cumulative period (years) in which have been registered the fatalities (36 years, until October 2011), C represents the worldwide wind power generation capacity at the time of societal risk technique application (200 GW, in October 2011), and P denotes the wind power generation capacity of a site (wind farm/park take arbitrarily). The results are plotted in a graph comprising the cumulative frequency of fatal accidents per MW per year versus the number of fatalities. For example, considering third parties (17) and direct partners (58), in 75 accidents there is 1 fatality. This is the most frequent occurrence among fatal accidents. Still, in a total of three accidents (in which resulted in six fatalities), there was four fatalities (two accidents) involving direct partners and two fatalities (one accident) related to third parties. Summarizing, there are more fatalities than accidents as some accidents have caused multiple fatalities. In most of the accidents occurred one fatality. Few accidents involve more than one fatality, being recorded once four fatalities occurred to third parties [24].

As illustrated in Fig. 5, two wind power generation systems (arbitrarily chosen) scenarios are considered for the societal risk technique application. Given the available data, it can be clearly seen that for 1 MW of installed capacity (all of) the risks stay conveniently in the acceptability area of the graph; conversely, the F–N curve for 100 MW is completely inside the ALARP area, demonstrating the direct relationship between the risk and the selected parameter (power generation capacity) for this study. The results of this risk analysis fall in the social acceptability boundaries (in particular adopted by the environmental agency of state of São Paulo, Brazil) [43]. Fatalities involving (at the same time) five individuals or more were not registered until the period considered (October 2011) in this investigation.

If new information has been made available from research, experienced accidents/incidents or changes in the way performance standards for safety critical systems are being fulfilled on the wind site, the ALARP evaluation, as an inherently dynamic process, needs to be regularly reconsidered [16].

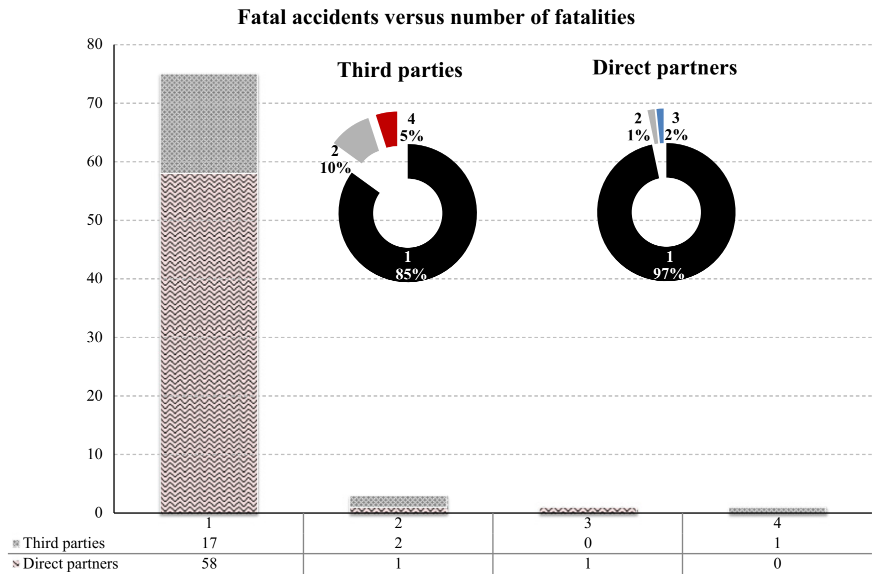

Fig. 4. Fatal accidents according to the number of fatalities (absolute and percentage) distributed according to the individuals involved (direct partners and third parties).

Table 1
Registered number of accidents *A* relative to the number of fatalities *N* involving 1, 2, 3 or 4 persons. The percentages in relation to the total number of accidents (80) are given in parenthesis.

Human victim	*N*				Total
	1	2	3	4	
Third parties	17 (21.25%)	2 (2.5%)	0 (0.00%)	1 (1.25%)	20 (25%)
Direct partners	58 (75.50%)	1 (1.25%)	1 (1.25%)	0 (0.00%)	60 (75%)
Total	75 (93.75%)	3 (3.75%)	1 (1.25%)	1 (1.25%)	80 (100.00%)

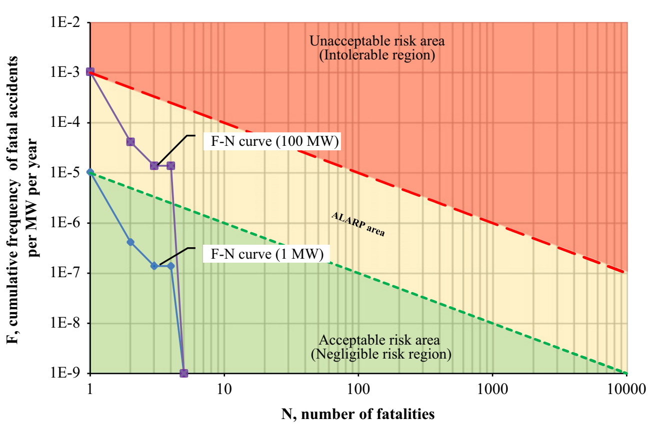

Fig. 5. Societal risk compared with regulatory risk criteria (acceptability limits adopted in Brazil [43]): F–N curves parameterized by specific installed wind power generation capacity.

4.1. Details of some facts

From a qualitative perspective, in this subsection some of the documented cases of wind turbine related to fatalities are pointed out [24] (until October 2011):

- The most documented type of fatality involving direct partners is due to fall (11), being also reported electrocution, tower collapse, tower crushing, servicing, ice falling, mounting, explosion, and maintenance
- Due to driver distraction, three fatalities involving third parties were documented; they occurred at the same place at distinct time intervals (i.e. three times)
- The only fatal accident involving four persons (third parties) at the same place and time was due to a plane crash
- There is only one fatal accident occurred to direct partners involving three workers at once
- Cases of suicide were documented involving direct partners as well as third parties.

5. Conclusion

Based on documented historical accident data, the quantitative measure of societal risk has been assessed for wind energy technology. The main consequences of accidents can be classified into two groups: damage to life (impacts on wildlife, human injury, fatal accidents) and damage to property (blade failure, miscellaneous, fire, structural failures, transport, icing). According to the accident profile observed at the wind industry the risk is characteristically physical in nature. Notably, the number of injuries/casualties involving third parties is not insignificant although it is much smaller than for direct partners. It is noteworthy that accidents involving more than one fatality occurred more often to third parties. Nonetheless, as the wind energy sector experiences advance in terms of installed capacity, the relative number of accidents tends to fall. Few accidents involve more than one fatality. There is a direct relationship between risk and wind turbine installed capacity as observed in F–N curves of the societal risk graph: the increase in capacity to generate energy demands improvement in security levels as the acceptable risk area is exceeded. Although zero risk is inherently unfeasible, since every action gives rise to a risk, it is a good practice to set targets for improving safety, provided that these targets must be achievable and reasonably practicable. As a concluding remark, it is expected that the societal risk could have their effectiveness improved by means of its combination with statistical analysis or neural network techniques, as well as another quantitative methodologies. Overall, the numbers are not large, the technology of the modern wind turbines is new, and, therefore, a greater data gathering (considering a longer time) would be needed to enable a deeper statistical analysis.

The societal risk technique provides good results on a case-by-case basis with the amount of data available for the wind energy industry.

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